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of

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for

ASYMMETRIC OPTICAL FOCUSING SYSTEM

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ASYMMETRIC OPTICAL FOCUSING SYSTEM

[001] This application claims priority to and the benefit of United States Provisional Patent Application Serial No. 60/423,014, filed on November 1, 2002, which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

[002] The present invention relates to laser diodes, and more particularly to optical focusing systems for a laser diode output.

2. Background Technology

[003] High power laser sources are used in a wide variety of applications, including pumping solid state lasers and fiber amplifiers, processing materials, providing optical energy for medical application, etc. In order to achieve a sufficiently high optical output, a high power semiconductor laser source can be implemented in a Master Oscillator Power Amplifier (MOPA) structure. A typical MOPA structure includes a diode feedback (DFB) laser as primary source, followed by a planar waveguide amplifier, both formed on the same semiconductor structure.

[004] The problem with the MOPA device is that its optical output beam is not only divergent (by different amounts in the vertical and horizontal planes of beam propagation), but it also has a very high degree of astigmatism. Figures 1A and 1B illustrate a conventional MOPA structure, with a laser diode portion 1 producing an optical output beam 2 that traverses through a planar amplifier portion 3 before exiting

the MOPA device. In the horizontal plane of beam propagation (*i.e.*, the plane of the amplifier portion 3), the optical beam 2 is allowed to spread laterally as it traverses through the amplifier portion 3 (*see* Figure 1A). However, in the vertical plane of beam propagation, the optical beam 2 is guided through the amplifier portion 3, and does not vertically spread until it exits the MOPA device (*see* Figure 1B). Thus, the optical beam 2 leaving the MOPA device has two different effective focal points of origin: one near the exit face of the MOPA (in the vertical plane), and one near the junction of the laser diode portion 1 and the amplifier portion 3 (in the horizontal plane). The difference between these focal points of origin is essentially the length of the amplifier portion 3. This mismatch in focal points of origin of the beam in the two orthogonal planes of beam propagation is commonly referred to as astigmatism.

[005] For most applications, the output of the MOPA needs to be focused to a small spot size (*i.e.*, small beam diameter) with very little if any astigmatism, and with a uniform numerical aperture (measure of divergence and convergence), in both orthogonal planes of beam propagation. For example, it is quite common to focus the MOPA optical beam into a single mode optical fiber having a symmetric transmission mode. It is well known that any given optical fiber has an acceptance numerical aperture associated therewith that if exceeded by an incident light beam would prevent all the light from being properly coupled into the fiber. Focusing optics for these applications must therefore compensate not only for the MOPA output divergence, but also for its astigmatism, in focusing the beam to a small symmetric coherent spot with the proper numerical aperture that matches that of the single mode fiber.

[006] In order to generate a greater amount of amplification, newer MOPA designs include longer amplifier portions, which produce greater astigmatism in the MOPA

optical beam. As the astigmatism of MOPA devices increases, it becomes more difficult to design and implement focusing systems that correct for such astigmatism and still provide the desired numerical aperture and spot size for the user's application. Conventional optical focusing systems used to correct large amounts of astigmatism utilize complicated arrangements of optical elements that are difficult to align, sensitive to misalignment, and costly to implement.

[007] There is a need for a simple, cost effective optical solution for correcting relatively large astigmatism in an optical source output beam that is easy to align and produces a symmetric spot size output having the desired numerical aperture with diffraction limited performance.

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SUMMARY OF THE INVENTION

[008] The present invention is a two element optical focusing system that focuses an astigmatic optical beam down to a desired diameter with a symmetric spot size and numerical aperture.

[009] The optical device of the present invention includes an optical source for producing an optical beam having spaced apart first and second focal points of origin in orthogonal first and second planes of beam propagation of the optical beam, respectively, a first lens disposed in the optical beam having a first optical focusing power in both the first and second planes of beam propagation, wherein the first lens is disposed at a first distance from the first focal point of origin for generally collimating the optical beam in the first plane of beam propagation and for focusing the optical beam down to a first beam diameter in the second plane of beam propagation at an image position located a second distance from the first lens, and a second lens disposed in the optical beam having a second optical focusing power in the first plane of beam propagation and generally no optical focusing power in the second plane of beam propagation, wherein the second lens is disposed at a third distance from the image position for focusing the optical beam down to a second beam diameter in the first plane of beam propagation at the image position.

[010] In another aspect of the present invention, an optical system focuses an optical beam into an input face of an optical fiber, where the optical beam has spaced apart first and second focal points of origin in orthogonal first and second planes of beam propagation of the optical beam, respectively. The optical system includes a first lens disposed in the optical beam having a first optical focusing power in both the first and second planes of beam propagation, wherein the first lens is disposed at a first

distance from the first focal point of origin for generally collimating the optical beam in the first plane of beam propagation and for focusing the optical beam down to a first beam diameter in the second plane of beam propagation at an image position located a second distance from the first lens, and a second lens disposed in the optical beam having a second optical focusing power in the first plane of beam propagation and generally no optical focusing power in the second plane of beam propagation, wherein the second lens is disposed at a third distance from the image position for focusing the optical beam down to a second beam diameter in the first plane of beam propagation at the image position.

[011] In yet another aspect of the present invention, a method of focusing an astigmatic optical beam includes the steps of producing an optical beam having spaced apart first and second focal points of origin in orthogonal first and second planes of beam propagation of the optical beam, respectively, placing a first lens in the optical beam having a first optical focusing power in both the first and second planes of beam propagation, wherein the first lens is placed at a first distance from the first focal point of origin for generally collimating the optical beam in the first plane of beam propagation and for focusing the optical beam down to a first beam diameter in the second plane of beam propagation at an image position located a second distance from the first lens, and placing a second lens in the optical beam having a second optical focusing power in the first plane of beam propagation and generally no optical focusing power in the second plane of beam propagation, wherein the second lens is placed at a third distance from the image position for focusing the optical beam down to a second beam diameter in the first plane of beam propagation at the image position.

[012] These and other features of the present invention will become more fully apparent from the following description and appended claims, or may be learned by the practice of the invention as set forth hereinafter.

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BRIEF DESCRIPTION OF THE DRAWINGS

[013] To further clarify the above and other advantages and features of the present invention, a more particular description of the invention will be rendered by reference to specific embodiments thereof which are illustrated in the appended drawings. It is appreciated that these drawings depict only typical embodiments of the invention and are therefore not to be considered limiting of its scope. The invention will be described and explained with additional specificity and detail through the use of the accompanying drawings in which:

[014] Figure 1A is a top cross-sectional view of a conventional MOPA device;

[015] Figure 1B is a side cross-sectional view of a conventional MOPA device;

[016] Figure 2A is a side cross-sectional view of the optical focusing system of the present invention, illustrating the vertical plane of beam propagation;

[017] Figure 2B is a top cross-sectional view of the optical focusing system of the present invention, illustrating the horizontal plane of beam propagation;

[018] Figure 3A is a side cross-sectional view of an exemplary embodiment of the optical focusing system of the present invention; and

[019] Figure 3B is a top cross-sectional view of the exemplary embodiment of the optical focusing system of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[020] The present invention is a simple, two element asymmetrical optical focusing system that corrects relatively large astigmatism in an optical beam and focuses it down to a small, symmetric spot size, with a symmetric numerical aperture, that could be launched directly into a single mode optical fiber. The optical focusing system is easy to align, and relatively insensitive to misalignment because it generally collimates the optical beam in the vertical plane of beam propagation.

[021] The optical focusing system of the present invention for an optical source 10 is shown in Figures 2A and 2B, and includes a first focusing element 12 and a second focusing element 14.

[022] The optical source 10 shown in the figures is a MOPA device having a laser diode portion 16 and an amplifier portion 18. However, it should be understood that optical source 10 can be any light source that produces (*i.e.*, generates or delivers) an optical beam having a relatively high astigmatism (significantly high separation between effective focal points of origin in orthogonal planes of beam propagation). The laser diode portion 16 includes an optical cavity 20 that produces an optical light beam 22 which is directed out into the amplifier portion 18. The amplifier portion 18 includes a planar wave guide cavity 24 that has a vertical dimension similar to that of the laser diode optical cavity 20, but a significantly larger lateral dimension compared to that of the laser diode optical cavity 20. Therefore, as the optical beam 22 traverses through amplifier portion 18, it is confined and does not expand significantly in the vertical direction (*see* Figure 2A) while it is not confined and does expand significantly in the lateral direction (*see* Figure 2B). Therefore, in the vertical plane of beam propagation shown in Figure 2A, the effective focal point of origin is approximately at the exit face

26 of the optical source 10. In the horizontal plane of beam propagation shown in Figure 2B, the effective focal point of origin is approximately where the laser diode and amplifier portions 16 and 18 meet. The two focal points of origin are separated by a distance D_1 that is essentially equal to the optical length of the amplifier portion 18.

[023] The first focusing element 12 is a symmetrical focusing lens, which means it has the same focal length F_1 (*i.e.*, same optical focusing power) in both the vertical and horizontal planes of beam propagation. Lens 12 is placed approximately one focal length F_1 away from the output face of the optical source 10 (*i.e.*, the focal point of origin in the vertical plane of beam propagation), so that the beam 22 is generally collimated in the vertical plane of beam propagation (*see* Figure 2A). In the horizontal plane of beam propagation, the beam 20 is focused down by lens 12 to a small spot size (*i.e.*, small beam diameter) at an image position I_p located at a distance D_2 from lens 12 (*see* Figure 2B). As explained in more detail below, D_2 is greater than F_1 .

[024] The second focusing element 14 is a non-symmetrical focusing lens (*e.g.*, a cylindrical lens), which means it has a focal length F_2 in the vertical plane of beam propagation but essentially no optical focusing power in the horizontal plane of beam propagation. Lens 14 is placed approximately one focal length F_2 away from the image position I_p (*i.e.*, a distance D_3 away from first lens 12), so that the collimated beam in the vertical plane of beam propagation is focused down to a small spot size at the image position I_p (*see* Figure 2A), while not providing any optical focusing power in the horizontal plane of beam propagation (*see* Figure 2B).

[025] Any appropriate user application can be positioned at the image position I_p . The user application shown as an example in Figures 2A and 2B, and used in the following discussion, is a single mode optical fiber 28 having an input face 29 disposed

at the image position I_p , whereby the optical beam 22 is coupled into optical fiber 28 for transmission to another location. However, it should be appreciated that the present invention is not limited to optical fiber applications at image position I_p .

[026] The selection of focal lengths F_1/F_2 and spacing D_2/D_3 for lenses 12 and 14 to achieve the proper spot size, numerical aperture, and astigmatism correction at image position I_p are determined from the following equations.

Numerical aperture N_A is defined as:

$$N_A = \sin \theta$$

where θ is the half angle of diverging or converging light. The converging light entering the optical fiber cannot exceed the acceptance numerical aperture for the fiber so that all of the light incident thereon can be properly coupled into the fiber without significant optical loss. In most cases, the numerical aperture of the optical beam exiting the MOPA exceeds the acceptance numerical aperture of the optical fiber. Thus, not only must the optical focusing system compensate for astigmatism, but it must also focus the beam down to a sufficiently small spot size for coupling into the optical fiber without exceeding the acceptance numerical aperture in either of the planes of beam propagation. This can be achieved so long as the magnification M of the optical system defined by first and second lenses 12 and 14 is sufficiently high, as described below.

[027] The magnification M of a single lens is defined as:

$$M = \frac{\text{lens to image distance}}{\text{lens to object distance}} \quad (2)$$

Thus, for lens 12 in the horizontal plane of beam propagation (see Figure 2B), magnification M_H is:

$$M_H = \frac{D_2}{F_1 + D_1} \quad (3)$$

[028] Moreover, for thin lens optics,

$$\frac{1}{\text{lens focal length}} = \frac{1}{\text{lens image distance}} + \frac{1}{\text{lens object distance}} \quad (4)$$

[029] Thus, for lens 12 in the horizontal plane of beam propagation:

$$\frac{1}{F_1} = \frac{1}{D_2} + \frac{1}{F_1 + D_1} \quad (5)$$

[030] For a pair of lenses with collimated light therebetween, the magnification is the ratio of the focal distances of the lenses. Thus, for lenses 12 and 14 in the vertical plane of beam propagation (see Figure 2A), magnification M_v is:

$$M_v = \frac{F_2}{F_1} \quad (6)$$

[031] In order for the light beam to have proper convergence characteristics at the image position I_p , the magnification of the optics between the optical source 10 and the optical fiber 28 should meet the following criteria:

$$M = \frac{N_A \text{ of the optical source output beam}}{\text{Acceptance } N_A \text{ of the optical fiber}} \quad (7)$$

where the N_A of the optical source output beam will most likely be different in the vertical and horizontal planes of beam propagation, and the acceptance N_A of the optical fiber will most likely be the same in the vertical and horizontal planes of beam propagation.

[032] Combining equations (3) and (7) for the horizontal plane of beam propagation yields:

$$\frac{D_2}{F_1 + D_1} = \frac{\text{Optical source output beam } N_A \text{ in horizontal plane of beam propagation}}{\text{Acceptance } N_A \text{ of the optical fiber}} \quad (8)$$

Combining equations (6) and (7) for the vertical plane of beam propagation yields:

$$\frac{F_2}{F_1} = \frac{\text{Optical source output beam } N_A \text{ in vertical plane of beam propagation}}{\text{Acceptance } N_A \text{ of the optical fiber}} \quad (9)$$

[033] Once a MOPA device (having known numerical apertures) has been selected, and the application requirements have been determined (*e.g.*, optical fiber with known acceptance N_A), the lens focal lengths and positions are easily calculated using the above equations to produce the desired convergence properties (*e.g.*, symmetric numerical aperture and spot size) at image position I_p . For example, lenses with focal lengths F_1 and F_2 can be selected to provide the proper magnification according to equation (9), and D_2 can be calculated using equation (8), where F_1 , F_2 , and D_2 can be used to position the lenses 12 and 14 and optical fiber input face 29 relative to the MOPA 10. Alternatively, if space considerations dictate a particular value for D_2 , then the requisite focal length F_1 can be calculated using equation (8), and the requisite focal length F_2 can be calculated using equation (9). If the lenses 12 and 14 have already been selected, then an appropriate optical fiber acceptance N_A can be determined using equation (9).

[034] The present invention is an asymmetrical optical system, with a single lens coupling system in one plane of beam propagation, and a two lens coupling system in an orthogonal plane of beam propagation. The optical system is a simple, elegant, low cost solution to a complicated optical problem because it uses only a pair of standard, widely available focusing lenses to couple highly astigmatic light into an optical fiber (or any other application) with a generally symmetric spot size and numerical aperture,

in a manner that is easy to align, relatively insensitive to misalignment, and with straight forward optical aberration correction.

[035] The asymmetrical optical system of the present invention is quite simple to align once the lenses and their spacing have been determined as discussed above. First lens 12 is initially aligned to the optical source 10 to produce generally collimated light in the vertical plane of beam propagation, and the input face of the optical fiber 28 is aligned to the focal point of the light in the horizontal plane of beam propagation. This is a straight forward, single lens coupling alignment, made even simpler given that the image spot size is important for only one plane of beam propagation. During the alignment of first lens 12, second lens 14 can be placed near its expected position in beam 22, but its exact position is not crucial because second lens 14 has no optical power in the horizontal plane of beam propagation. Then, the position of second lens 14 is adjusted to focus the collimated light in the vertical plane of beam propagation down to a spot at the optical fiber input face. This is also a straight forward alignment given that only one lane of beam propagation is affected and light in this plane is collimated.

[036] While the above equations can be used to select and position appropriate lenses 12 and 14, optical simulation (ray-tracing) software (which is well known in the art) can also be used as well. Using the two lens configurations of the present invention and the above equations as a starting point, an optical designer using ray-tracing software can dynamically manipulate the optical variables (D_1 , D_2 , D_3 , F_1 , F_2 , numerical apertures, etc.) to produce simulations of the collimated/focused beam portions of the present invention, resulting in the optimal beam spot size and numerical aperture with minimal aberration at the image position I_p for the user's application.

[037] Figures 3A and 3B illustrate an example of the coupling system of the present invention that has been designed and reduced to practice using the above equations and ray-tracing software. Optical source 10 in this example is a MOPA device having 470 microns (air equivalent) of astigmatism, with an optical output beam having a half angle divergence of about 30 degrees. Thus, according to equation (1), this MOPA device has a numerical aperture of 0.5. The optical application is a single mode optical fiber 28 having an acceptance numerical aperture of 0.13. Therefore, the optical coupling system should have a magnification of at least 3.84 as calculated by equation (7). In order to provide some tolerance in this example optical focusing system, the target magnification is rounded up to 4.0.

[038] In order to achieve the target magnification and adequately compensate for the 470 microns of astigmatism, a double aspheric lens is selected as the first lens 12, and a rod lens is selected as second lens 14. The selected double aspheric lens is a microlens model number 310A, obtained from the optics division of Hoya Corporation. This microlens has a 2.7 mm diameter, and a 1.08 mm thickness. It is selected because of its high quality and low aberration, as well as for having optical specifications that provide the desired (4.0) magnification in the horizontal plane of beam propagation while collimating the light in the vertical plane of beam propagation. The rod lens 14 has a 4 mm diameter.

[039] The positions of the optical elements are as follows. The front face 12a of double aspheric lens 12 is positioned 0.693 mm away from the output face of the MOPA device 10, in order to generally collimate the light in the vertical plane of beam propagation. At this position, in the horizontal plane of beam propagation, the double aspheric lens 12 produces a focused beam of desired diameter at a distance of 7.392 mm

from the rear face 12b of double aspheric lens 12. The input face 29 of optical fiber 28 is therefore disposed at this image position I_p . The back face 14b of rod lens 14 is positioned 1.249 mm away from image position I_p (and thus the front face 14a of rod lens 14 is positioned 2.143 mm from the back face 12b of double aspheric lens 12), in order to properly focus the collimated light in the vertical plane of beam propagation at the image position I_p . With these optical elements so positioned, the optical output of the MOPA device is focused down to a generally uniform spot size and numerical aperture at image position I_p .

[040] It is to be understood that the present invention is not limited to the embodiment(s) described above and illustrated herein, but encompasses all variations falling within the scope of the appended claims. For example, the magnification calculated by equation 7 is the minimum magnification needed to properly focus the light beam into the optical fiber. In actuality, greater magnifications will work as well, which gives workable tolerance to the optical focusing system. Therefore, equations (8) and (9), respectively, can be rewritten as:

$$\frac{D_2}{F_1 + D_1} \geq \frac{\text{Optical source output beam NA in horizontal plane of beam propagation}}{\text{Acceptance NA of the optical fiber}} \quad (10)$$

$$\frac{F_2}{F_1} \geq \frac{\text{Optical source output beam NA in vertical plane of beam propagation}}{\text{Acceptance NA of the optical fiber}} \quad (11)$$

Equations (10) and (11) also take into consideration the fact that the optical beam can be focused into the optical fiber with a numerical aperture that is well under the acceptance numerical aperture (*i.e.*, acceptance numerical aperture represents the maximum angle of convergence that the optical fiber will accept).

[041] The present invention may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the invention is, therefore, indicated by the appended claims rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

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